EFFECT OF DIE PATTERN ON EXPLOSIVELY FORMED FUSE PERFORMANCE*

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Abstract

Explosively formed fuse (EFF) devices are opening switches for high explosive pulsed power (HEPP) applications. Such switches have been operated at currents up to 25 MA, voltages up to 500 kV, and power over 3 TW in our large-scale HEPP systems. The switch consists of a conducting foil that is driven by high explosives into a dielectric die consisting of extrusion anvils and gaps that separate them. The switch develops resistance as the foil is extruded. We have conducted tests with many foils, and many die materials and patterns. We have also performed calculations using both 2-D hydrodynamic (hydro) and magneto-hydrodynamic (MHD) codes of switches with the different die patterns. Dies with more massive corners at each extrusion position develop resistance faster, and tend to have more pronounced features in the resulting R(t) curves. In addition, the explosive drive is important as is the shape and density of the anvil bottom. These data and calculations will be discussed, along with what we have learned from MHD calculations. To date, we have been unable to calculate accurate R(t) curves accurately from first principles with MHD codes, but have gained increased insight into performance.

I. INTRODUCTION

Over the last two decades, explosively formed fuse (EFF) opening switches have been used to divert current in high explosive pulsed power (HEPP) experiments [1][2][3]. Usually, in these experiments, a large current (10-25 MA) is switched to a low impedance load. The transferred current is determined by the ratio of storage inductance to load inductance. The resistance of the fuse determines the voltage in the circuit and the details of the resistance as a function of time, R(t), are extremely relevant for modeling efforts and for predictive capabilities, but the physical mechanisms involved in the resistance change are not well understood. Previous papers have dealt with the effects of varying fuse material thickness and material metallurgy. Other studies have dealt with the die material density. All these have provided insight toward enhanced understanding of the fuse dynamics. However, quantitative modeling of EFF performance with magneto-hydrodynamic (MHD) codes has been slow, and much of our understanding regarding the operating principles of EFF switches still comes from small-scale experiments. Due to the relatively high cost, and the need for numerous experiments, the detailed physics experiments must be done with small scale systems rather than a "full-up" system with very high current. The aim is to determine the shape of the resistance curve and to understand the mechanisms that

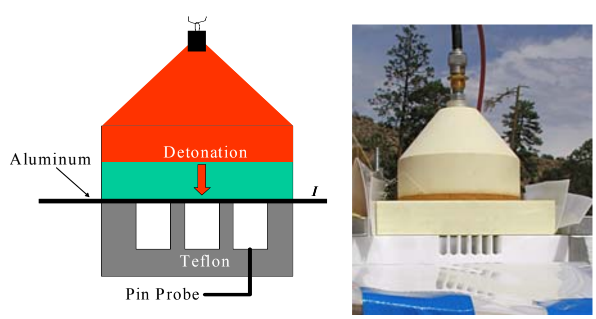

Figure 1 Illustration and photograph of small scale EFF test. The groove bottoms in the photograph show one of the V-groove designs that we tested.

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14. ABSTRACT
Explosively formed fuse (EFF) devices are opening switches for high explosive pulsed power (HEPP) applications. Such switches have been operated at currents up to 25 MA, voltages up to 500 kV, and power over 3 TW in our large-scale HEPP systems. The switch consists of a conducting foil that is driven by high explosives into a dielectric die consisting of extrusion anvils and gaps that separate them. The switch develops resistance as the foil is extruded. We have conducted tests with many foils, and many die materials and patterns. We have also performed calculations using both 2-D hydrodynamic (hydro) and magneto-hydrodynamic (MHD) codes of switches with the different die patterns. Dies with more massive corners at each extrusion position develop resistance faster, and tend to have more pronounced features in the resulting R(t) curves. In addition, the explosive drive is important as is the shape and density of the anvil bottom. These data and calculations will be discussed, along with what we have learned from MHD calculations. To date, we have been unable to calculate accurate R(t) curves accurately from first principles with MHD codes, but have gained increased insight into performance.

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modify the resistance curve shape so that future predictions can be made.

Fig 1 shows a generic small scale experiment. These experiments were normally done with current of approximately 500 KA in a conductor 6.4 cm wide. A plane-wave detonation system was used to drive the EFF conductor (aluminum) into the die. The current and

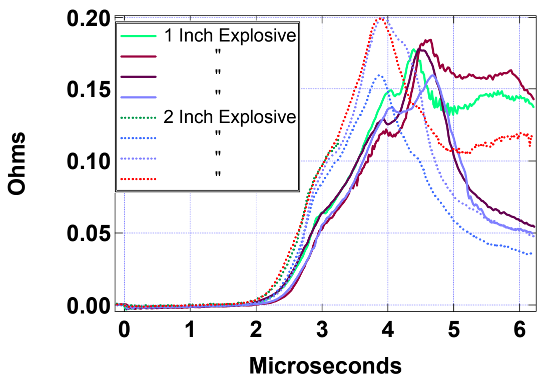

Figure 2. Resistance profiles with 1 inch and 2 inch HE drive.

voltage are measured and recorded on digitizers. Experiments are typically designed to match the electrical and physical conditions of some full-scale switch. In these cases, the die patterns and the current densities are adjusted to match that of a full-scale experiment.

We have performed many small scale experiments to study various switch parameters. These tests were frequently conducted to answer specific questions for a specific application. Our growing knowledge of switch characteristics has uncovered parameters that initially were deemed unimportant, but had a significant effect on the resistance. For example, current/width (I/w) did not seem important in early work, but after a large amount of data for similar configurations has been collected, the trend for resistance to decrease with increasing I/w is demonstrated[3]. Another example is demonstrated in figure 2. Two different initiation systems were available to us and one used one inch of explosive and the other 2 inches. The hydrodynamics calculations did not show any relevant difference and therefore, the two systems were used interchangeably until the large collection of data showed a consistent difference as seen in the figure. Some effect of I/w may be present in the data shown, but there is one curve in the 2 inch set that has larger current than some of the curves in the 1 inch set. As a result of such subtle differences we frequently have only small data sets to support the points we make, or we must extrapolate/or interpolate from results at one level to a data set at another.

II. EXPERIMENTS AND CALCULATIONS

In a series of previous experiments, a pin probe was used to determine the arrival time of the fuse material at the bottom of the die groove. For 12.7 mm deep grooves, the beginning of the resistance rise and the time that the aluminum hits the bottom are approximately 2 µsec. This correlation indicates that, perhaps, the resistance change is strongly related to the geometry at the bottom of the grooves and to the details of the fuse hydrodynamics. This suggested a new series of studies where “U-shaped” and “V-shaped” features were machined at the bottom of the die. Again, the fuse material is forced into the groove and the resulting resistance profiles are qualitatively compared to the hydro calculations. High resolution hydro calculations suggest violent stretching and material “swirls” appear during the time period when the aluminum hits the bottom of the groove and additional features occur in calculations for U and V bottoms that appeared to be easily recognized in experimental data.

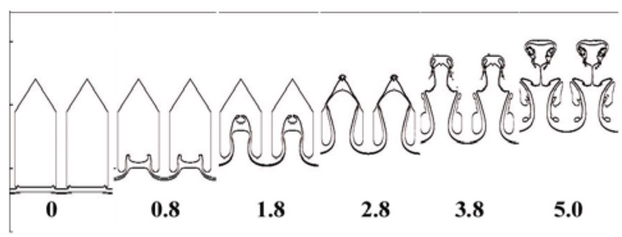

Figure 3. Hydro calculation of dynamics for EFF with 60 degree groove in die.

Because of the suspected importance of interactions of the foil and the switch bottom, we ran hydro calculations of configurations of both V and U shaped bottoms. Figure 3 shows the calculated hydro motion of the fuse material due to the V shaped grooves. The calculations show that material rebounds off the side of the V groove and stretches very rapidly. It then finally collides in the center, and therefore possibly generates electrical shorting, eliminating the resistive contribution

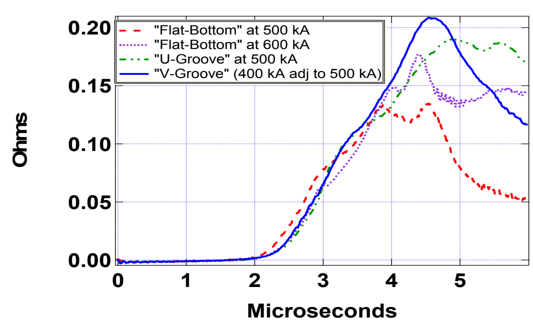

Figure 4 Resistance profiles from U and V bottomed dies compared to flat bottomed configurations.

due to the material above this point. Since we believed that this is easily diagnosable, we conducted experiments with both V and U shaped groove bottoms. If the rebounding material, as seen in figure 3 at 5 µs., or the material that goes deep into the groove, has a strong effect on the total resistance, then the effect should be observable and should show up somewhere between 4 and 5 µs in our experiment. The curves, shown in figure 4, are not appreciably different in early times, and do not show such shorting out feature at around 5 µs. Therefore, it seems that there is not a major enhancement due to the shape of the bottom, and further that most of the resistance appears to be along the "mushroom," which is what we have labeled the extruded material flowing into the groove over the anvil.

To scope out the control we might have on the shape of R(t) by varying the anvil thickness, we conducted a few tests using anvils 2 mm wide separated by 7.5 mm gaps and 1.5 mm wide with 6 mm gaps. The data shown in figure 5 confirm what we suggested in previous publications. As the anvil thickness increases, the initial rise becomes more abrupt. Thickening the anvil even more than shown here leads to further steepening of the curve. A plot of R(t) for a 3 mm x 9 mm die shows an even more abrupt rise to a more pronounced shoulder. The data, however, were taken at different I/w conditions than for the curves shown here and plotting them together may lead to erroneous conclusions about the details. Therefore, additional, well controlled, tests must be done to verify these intricate details.

We have conducted a few tests of small scale EFFs

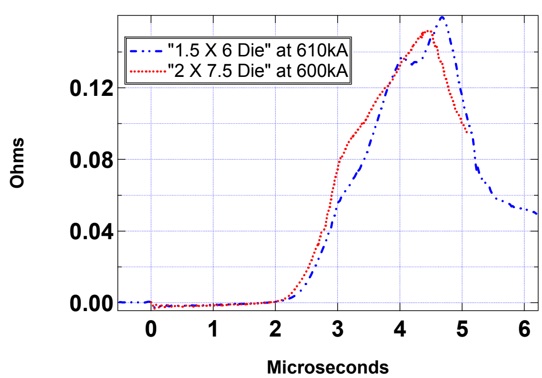

Figure 5. Resistance profiles for dies with 1.5 mm anvils and 6 mm deep grooves and 2 mm anvils and 7.5 mm deep grooves.

with deeper grooves than the 12.7 mm standard. These indicate that the shape of the curve changes as the position of the bottom changes. In particular, these tests have tended to follow an exponential rise until experiencing a voltage driven failure. Deep grooves typically add inductance to a switch, and are undesirable in practical designs. In order to see if a low density foam in the die bottom would serve the same purpose as making the groove deeper, we ran one experiment in that configuration. The foam was 0.5 g/cc CH material, and had grooves in it to hold 1.5 mm Teflon anvils. The data, shown in figure 6, show the same effect in this test as

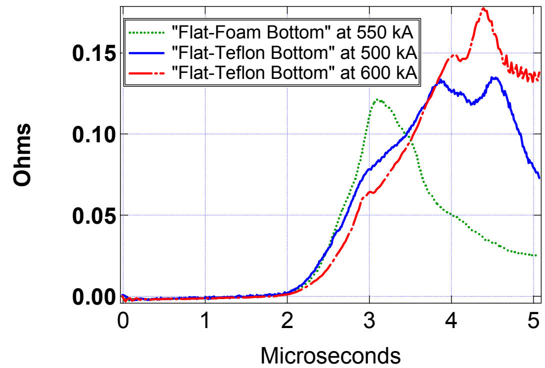

Figure 6. Resistance profile for foam bottomed die compared to two Teflon bottomed switch experiments.

observed in experiments with deeper grooves. The resistance decrease seen just past 3 µs is due, as in "deep groove" tests, to the switch developing ~60 KV. This is the limit that our small scale devices will withstand. Such problems are typically overcome in full-scale cylindrical devices. Since most pulsed power experiments are done in that geometry it is important to determine how long the observed shape of the resistance rise will persist in this, or deeper groove designs in cylindrical switches.

III. CONCLUSIONS

EFF opening switches represent an important technology for HEPP applications. As seen in figure 7,

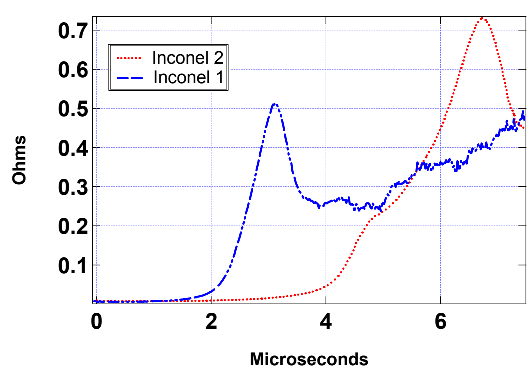

Figure 7. Inconel 1 carried 320 kA through a 17 mil thick foil and used a flat bottomed die with 1.5 mm anvils and 6 mm grooves that were 12.7 mm deep. Inconel 2 carried 409 kA through 34 mils of Inconel using a flat bottomed die with 3.2 mm anvils and 12.7 mm wide grooves that were 12.7 mm deep.

we can produce a wide range of R(t) profiles to meet a multitude of needs. The two curves are from tests using Inconel 625 for a conductor, with Teflon dies. Inconel 1 carried 320 kA through a 17 mil thick foil and used a flat bottomed die with 1.5 mm anvils and 6 mm grooves that were 12.7 mm deep. Inconel 2 carried 409 kA through 34 mils of Inconel using a flat bottomed die with 3.2 mm anvils and 12.7 mm wide grooves that were 12.7 mm deep. Coaxial switches will hold off over 9 kV/cm and operate at linear current densities up to 0.2 MA/cm width. Small scale EFF experiments still represent a meaningful tool for examining switch variations, and we have found many important parameters. We have discussed die design and HE drive in this paper. Tasker [4], in this conference, has discussed other parameters and variables. Unfortunately, MHD calculations are still not adequate to provide reliable R(t) profiles, and we must still use them and hydro-code results to guide us in obtaining desired profiles, and follow up with careful experiments. Some configurations require coaxial designs for optimum results.

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